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FIRE Aircraft Observations of Horizontal and Vertical Transport in Marine Stratocumulus

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INTRODUCTION

A major goal of research on marine stratocumulus is to try to understand the processes that generate and dissipate them. One approach to studying this problem is to investigate the boundary layer structure in the vicinity of a transition from a cloudy to a cloud-free region to document the differences in structure on each side of the transition. Since stratiform clouds have a major impact on the radiation divergence in the boundary layer, the transition from a cloudy to a clear boundary layer is a region of large horizontal inhomogeneity in air temperature and turbulence intensity. This leads to a considerable difference in horizontal and vertical transports between the cloudy and cloud-free regions.

We use measurements from the NCAR Electra aircraft during Flights 5 (7 July 1987) and 10 (18 July 1987) of FIRE for this purpose. Flight 5 coincided with a Landsat overflight, and was designed to investigate the transition across a well-defined N-S cloud boundary, since the Landsat image can document the cloud cover in considerable detail. Turbulence legs were flown about 60 km on both sides of the cloud boundary. Flight 10 was flown at night in an area of scattered small cumuli and broken cloud patches.

DISCUSSION OF OBSERVATIONS

Figure 1 shows data from two soundings, about 200 km apart, from Flight 5. The sounding on the left was taken in an area covered with a stratiform deck; the sounding on the right was in a cloud-free region. Profiles of liquid water content, potential temperature, and total water mixing ratio are shown. As can be seen in the stratiform sounding, there are sharp changes in potential temperature and total water mixing ratio at the inversion, whereas in the clear-air sounding the changes are gradual. These differences are a common feature of the cloudy and cloud-free soundings observed during both the Dynamics and Chemistry of Marine Stratocumulus (DYCOMS) experiment and FIRE.

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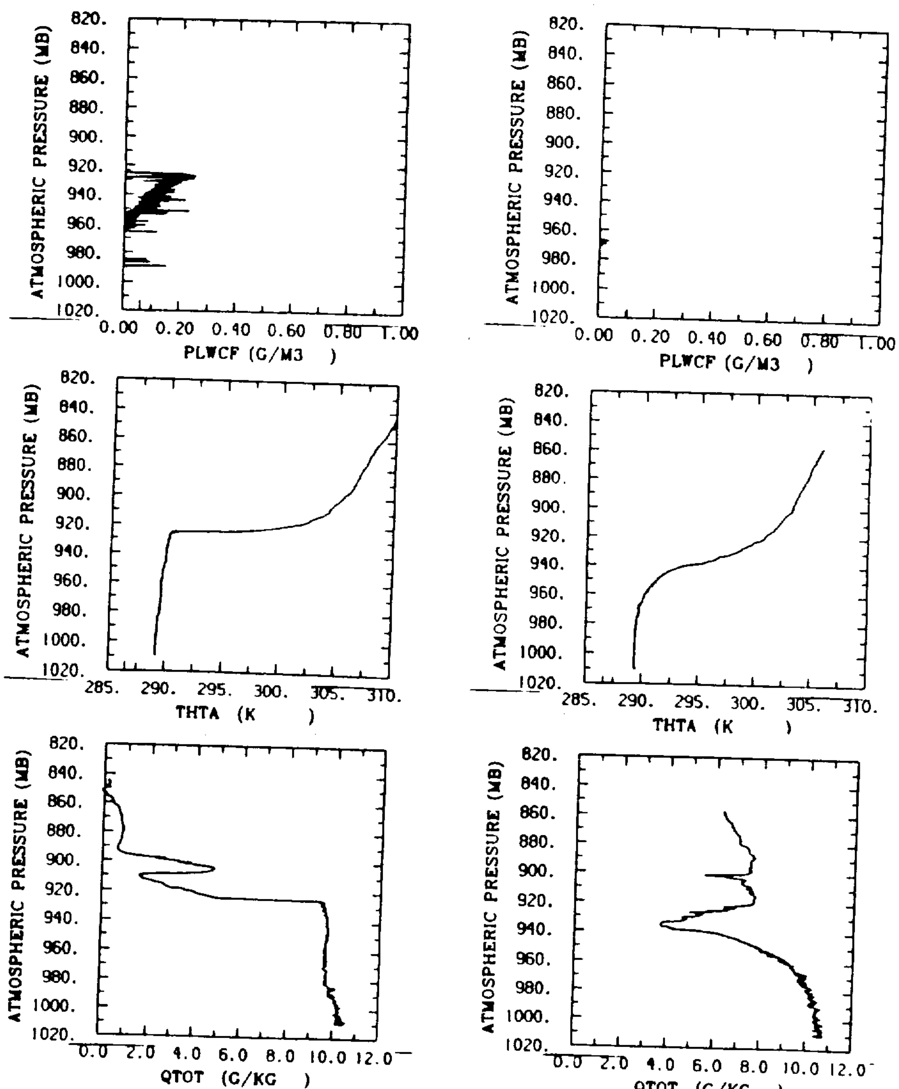

Figure 1. Profiles of liquid water content (PLWCF) from a Particle Measuring Systems FSSP, potential temperature Θ (THTA), and total water (vapor and liquid) mixing ratio (QTOT).From flight 5; 7 July,1987.

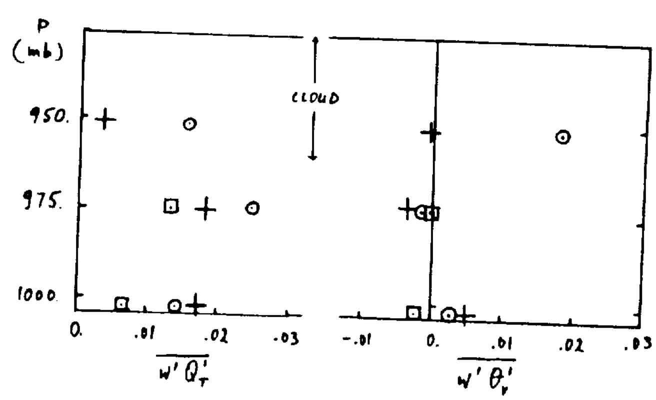

Figure 2. Total water and buoyancy fluxes measured by the Electra on flight 5, 7July 1987. The circles and squares represent fluxes from stratiform regions, the crosses data from cloud-free regions. For further explanation see text.

Figure 2 shows vertical moisture and buoyancy fluxes[1] measured during constant altitude flight legs on this day. The circles and squares represent data from stratiform regions, the crosses are data from clear air regions. At the two lowest levels (at 1010 and 975 mb), the squares represent portions of the flight leg where the sea surface temperature, measured by a surface temperature radiometer, was in the 15.0-15.8 C range; the circles and crosses correspond to a sea surface temperature in the 15.7-16.5 C range. As expected, the fluxes show some dependence on the sea surface temperature at the two lower flight levels. The buoyancy flux at 975 mb, however, is very small compared to that in cloud, which indicates that the surface buoyancy flux is likely to be relatively unimportant in the turbulence energy budget of this boundary layer. The upper level (950 mb) flight passed through the stratiform deck, and there the sea surface temperature could not be measured. In cloud, the buoyancy flux rises because of radiational cooling near cloud-top, which enhances mixing and entrainment at cloud top; consequently the moisture flux in cloud is also enhanced. By comparison, in the cloud-free region the moisture and buoyancy fluxes are negligible at 950 mb. As a result, there is little mixing and the temperature stratification is more stable (Fig. 1).

It is possible that at least some of the differences between the cloudy and cloud-free soundings in Fig. 1 are due to differences in horizontal advection. That is, the air in the cloudy region may have a different origin and have different thermodynamic properties than that in the cloud-free region. To minimize the effect of advection we examine several short soundings from Flight 10, where adjacent cloudy and clear areas were traversed in several up and down passes, as sketched in Fig. 3.

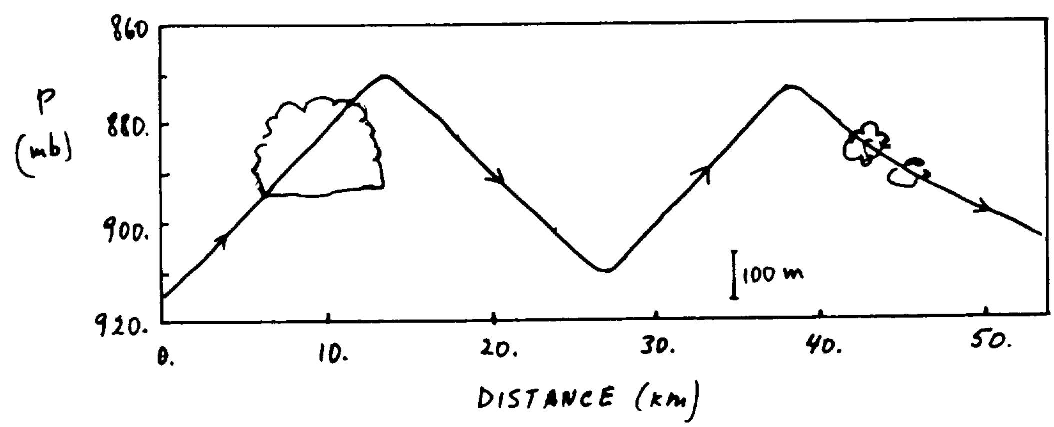

Figure 3. Sketch of the flight pattern used in Fig.4.

Soundings from the above passes are shown in Fig. 4. The plots show liquid water content, potential temperature, total water mixing ratio, vertical velocity, east velocity component, and north velocity component. As in the sounding in Fig. 1, here too

[1] i. e. $\overline{w'q'}$ and $\overline{w'\theta_v'}$, where w is vertical velocity, q the total water mixing ratio, θ_v the virtual potential temperature, the prime indicates departures from a least squares linear fit to the time series, and the overbar an average over a horizontal flight segment.

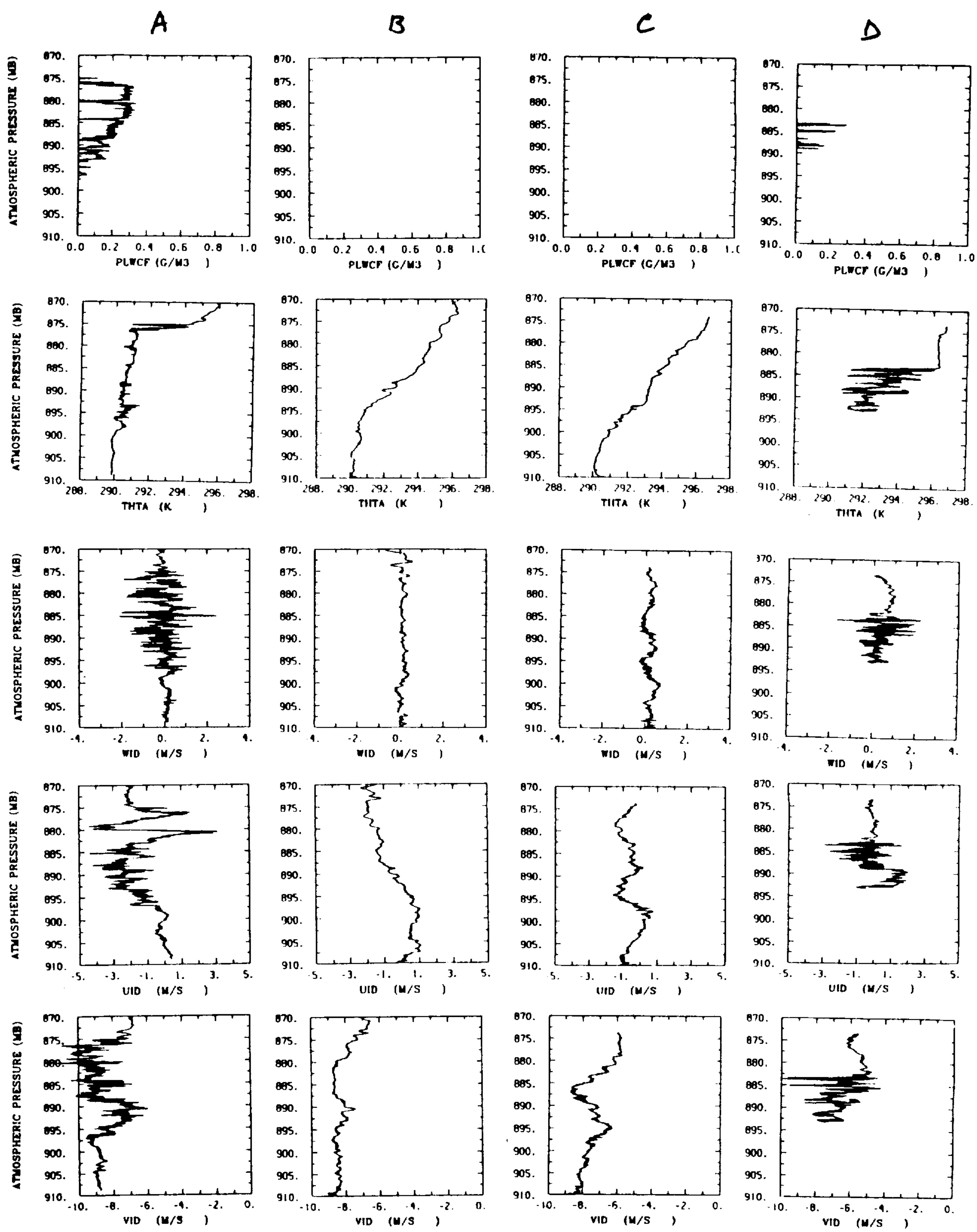

Figure 4. Profiles of liquid water content (PLWCF), potential temperature (THTA), vertical velocity (WID), east velocity component (UID), and north velocity component (VID) from Flight 10, 18 July 1987.

the clear-air temperature and moisture profiles change gradually with height (B and C), whereas in the presence of cloud or cloud patches there are abrupt changes in temperature and moisture at the inversion (A and D).

Comparing the first two soundings we note that the temperature in the cloudy air is significantly colder than in the adjacent clear air. The maximum difference in temperature reaches 4 K just below the inversion, at 875 mb, where the horizontal separation between the two soundings was only about 4 km. Clearly, such a temperature difference can be expected to lead to a circulation that would tend to reduce the difference. This instability can be viewed in terms of a simple situation, described by Margulis (1906) and often discussed in textbooks (for example, Hess, 1958), where two airmasses of different temperatures are side-by-side. Seeking a stable configuration, the airmasses then rearange themselves so that the colder air rests below the warmer air. It can be shown from energy balance that the velocity of such a circulation is of the order of

$$V = \frac{1}{2} g h \frac{\Delta\theta_v}{\theta_v}$$

where g is the gravitational acceleration, and $\Delta\theta_v$ is the virtual potential temperature difference between the two airmasses, initially extending over a height h. For the present case $\Delta\theta \sim 3\text{K}$ and $h \sim 200\text{m}$, so that the mean velocity $V \sim 2\text{m s}^{-1}$, which is well within the range of the present observations. Thus we expect that motions due to instabilities at the cloud and clear-air interfaces contribute to the velocity fluctuations. Since they tend to move cloudy air downward and under the adjacent cloud-free air, they likely erode the cloud edges and may lead to dissipation of the cloud.

In the last sounding the aircraft encountered a few turbulent cloud patches below an inversion located about 8 mb lower than the inversion in the first sounding. Below the inversion there are large fluctuations in temperature but, unlike the first sounding, the temperature fluctuations are positive as well as negative with respect to the nearby clear-air temperature profile. Thus, while there are large temperature instabilities locally, the region as a whole is more stable with respect to the nearby clear-air temperature profile than the cloud region encountered in the first sounding. It is likely that this sounding represents the dissipating stages of a cloud region which earlier may have been similar to that encountered in the first sounding.

REFERENCES

Hess, S., 1958: Introduction to theoretical meteorology. Holt, Rinehart and Winston, New York; pp. 297–302.

Margulis, M., 1906: Zur Sturmtheorie, Met. Zeit., 23, pp. 481-497.